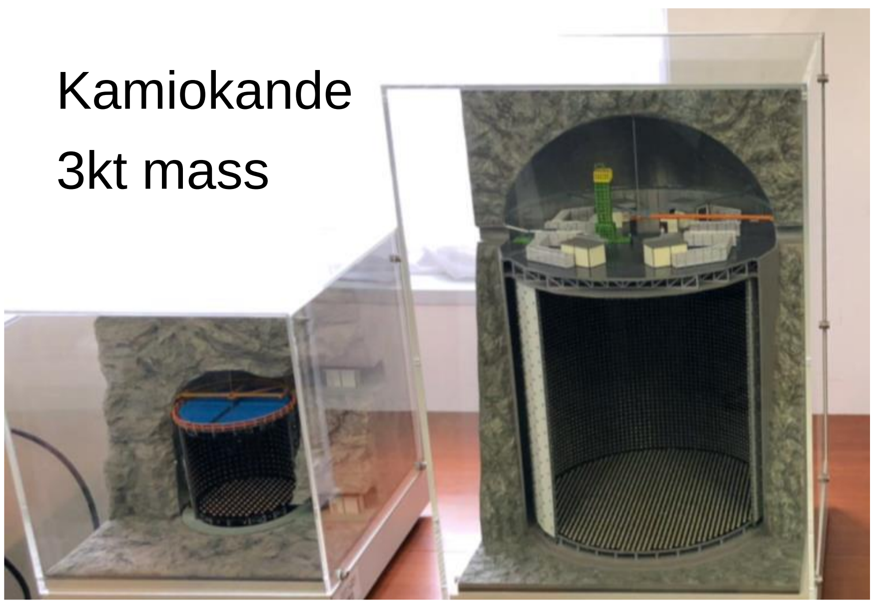
Long-baseline neutrino oscillation program at Hyper-Kamiokande

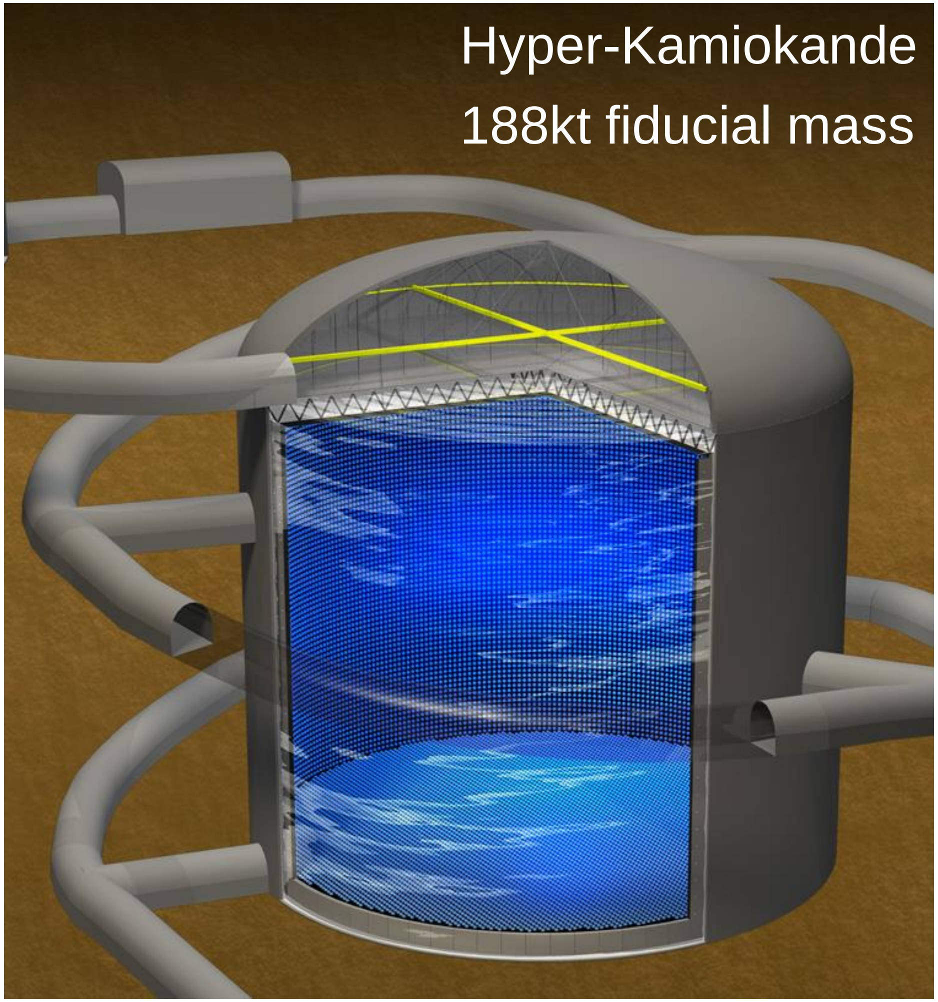
Mark Scott

Water Cherenkov detectors in Kamioka

Super-Kamiokande
22.5kt fiducial mass

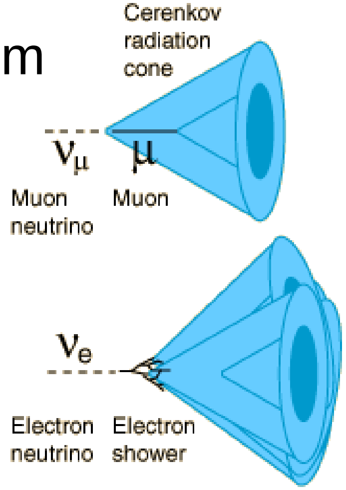
Kamiokande
3kt mass

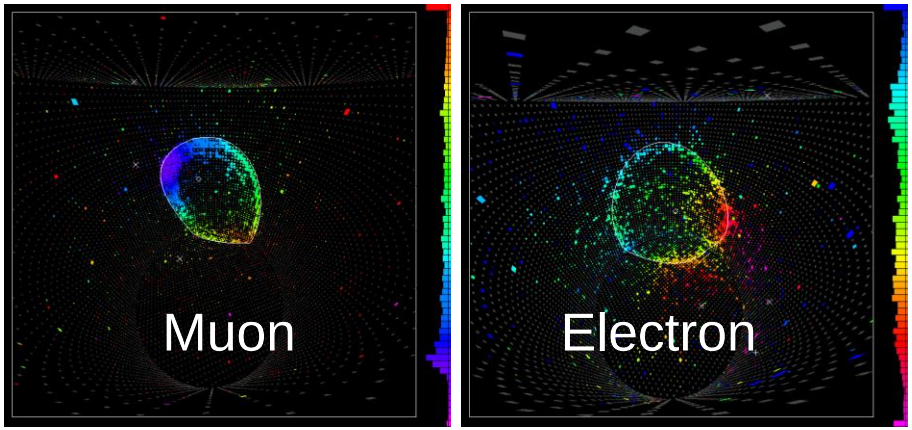


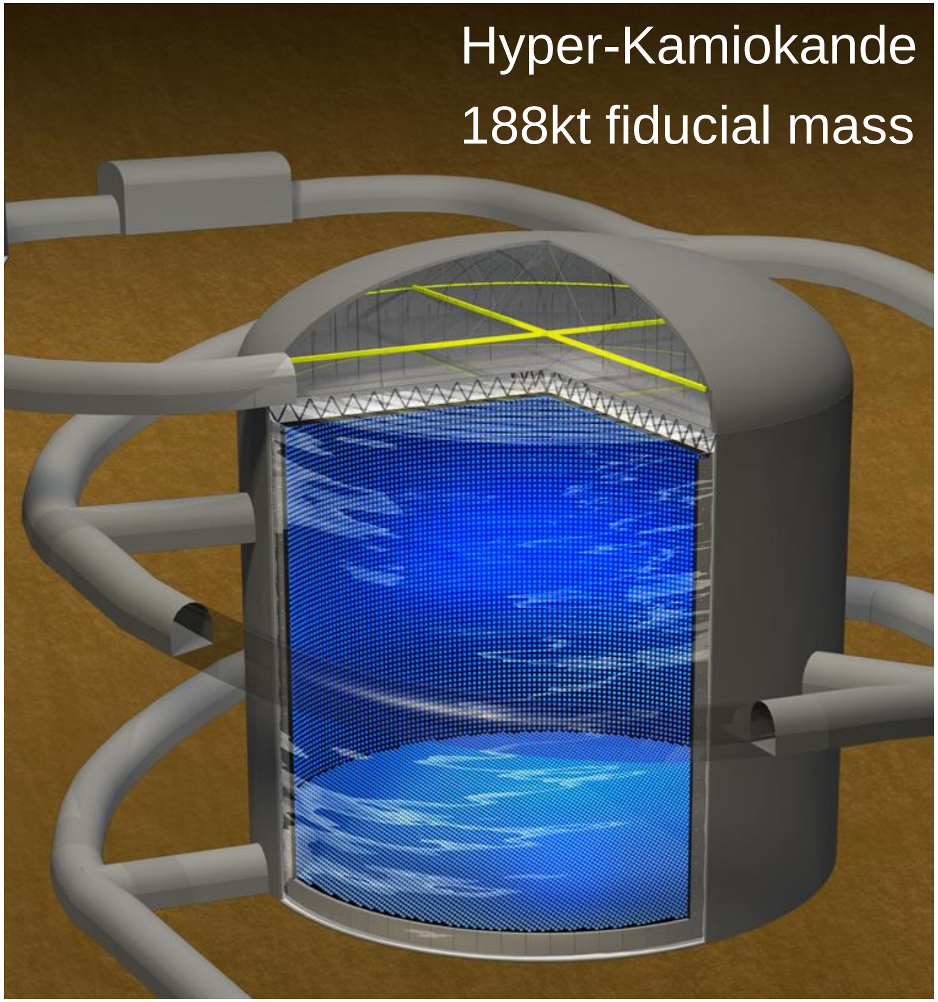


Water Cherenkov detectors in Kamioka

- Cherenkov ring from charged particles
- >99% μ/e separation
- Momentum and direction reconstruction

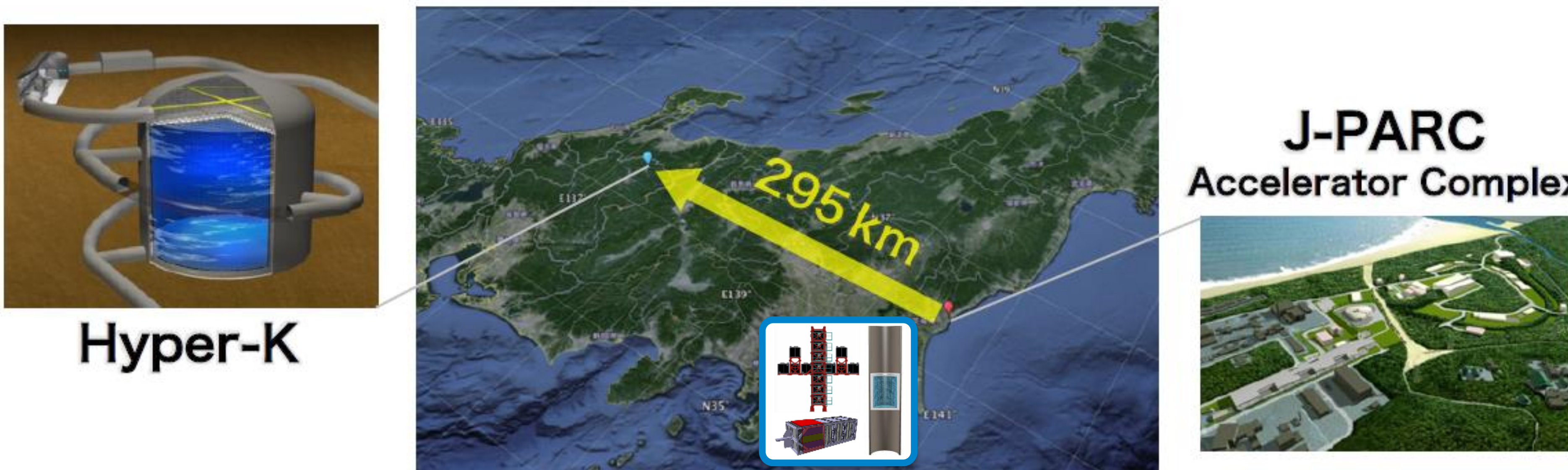






Hyper-Kamiokande experiment

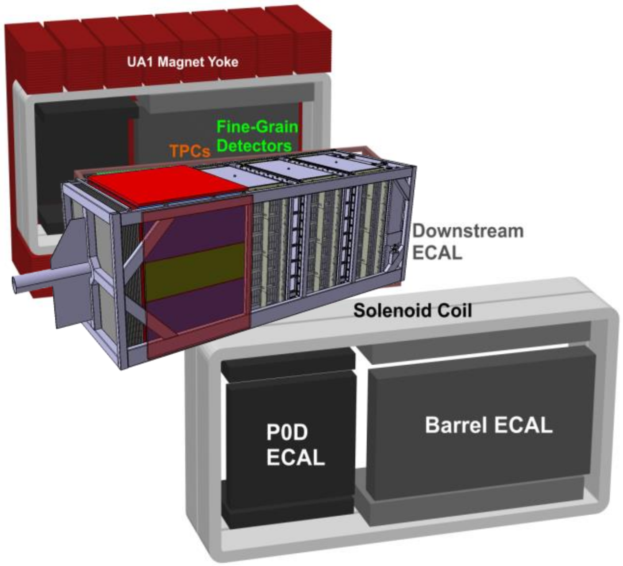
- **Factor 20 increase in statistics compared to T2K**:
  - Upgrade of the J-PARC neutrino beam to 1.3 MW
  - New far detector with 188kt fiducial volume
- New intermediate detector and inherited upgraded near detectors
- Improved photosensors with twice the quantum efficiency

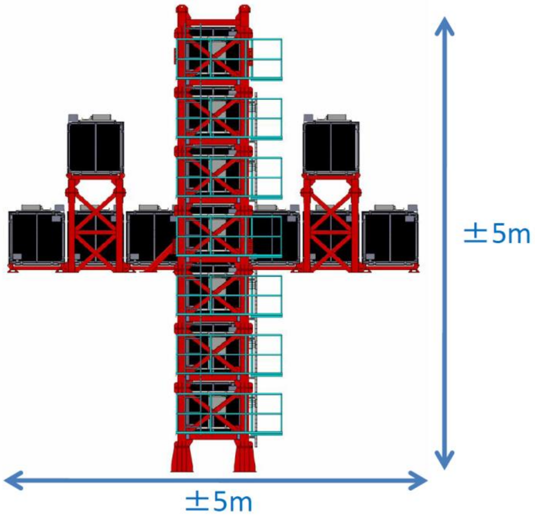


Near detector suite

- Off-axis near detector: 2.5 degrees off-axis, magnetized, high granularity plastic scintillator target, TPCs for particle kinematics
  - High statistics, measure hadronic system in scintillator, can identify neutrinos vs anti-neutrinos

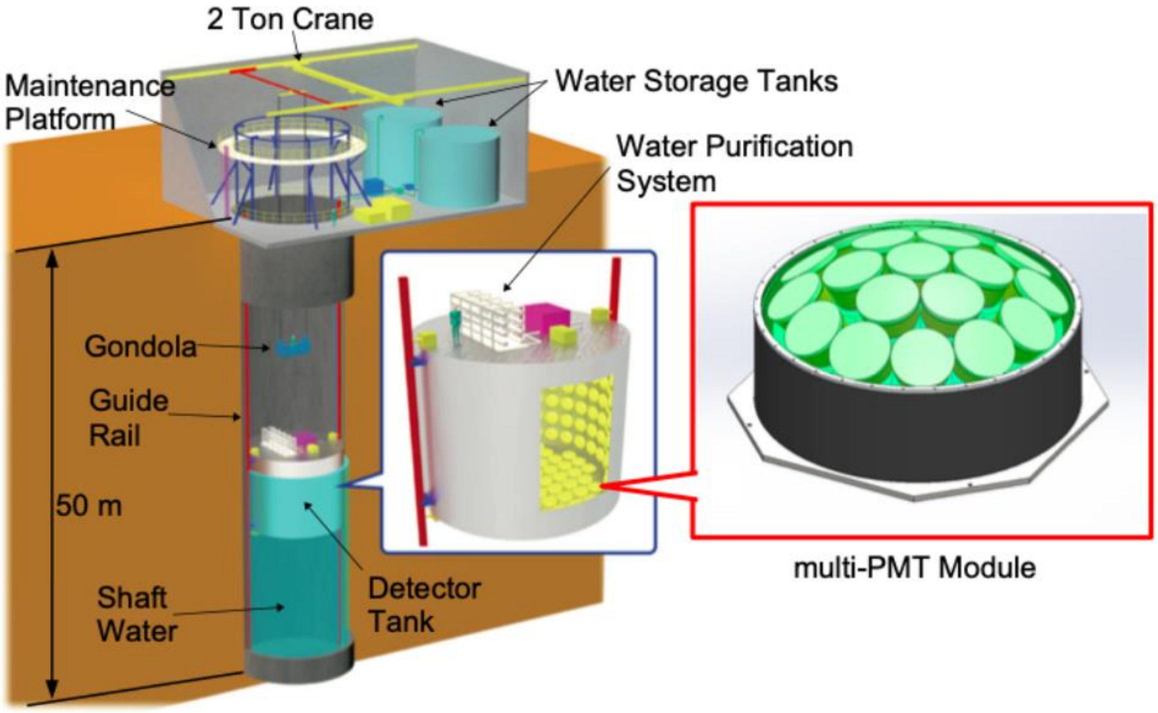
- On-axis detector (INGRID)
  - Plastic scintillator and iron plates
  - Gives beam direction and monitoring





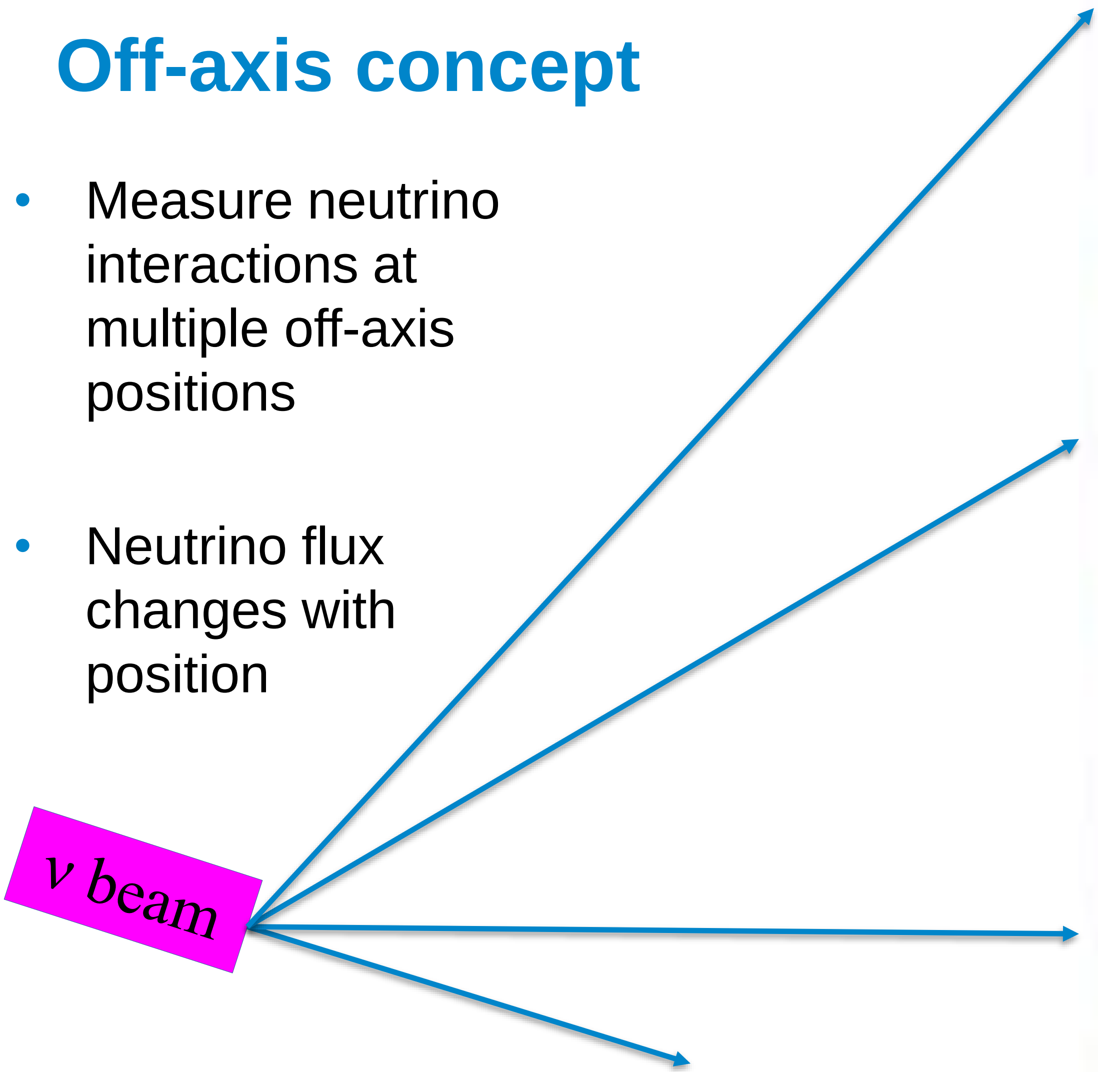
Intermediate Water Cherenkov Detector (IWCD)

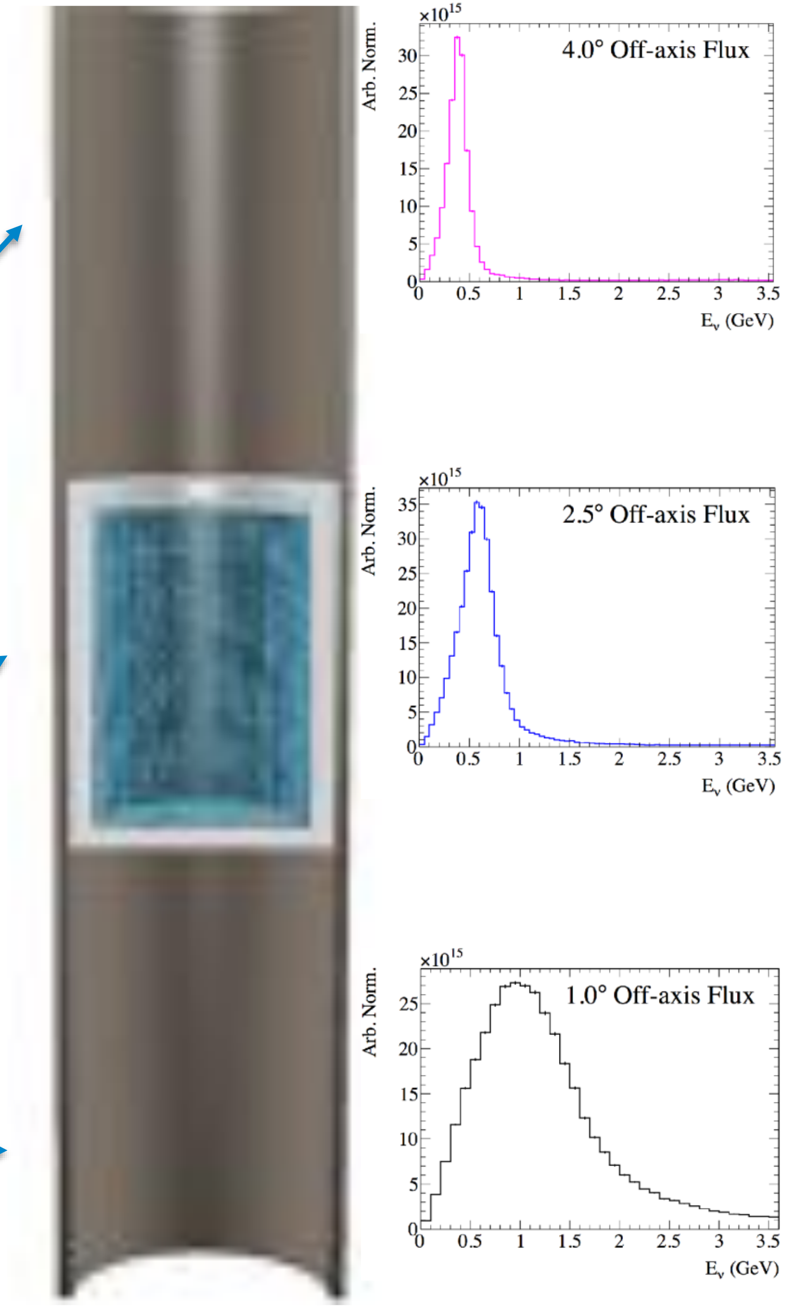
- Approx. 600-tonne water Cherenkov detector located ~1km from beam production point
- Movable to different off-axis angles



Off-axis concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position

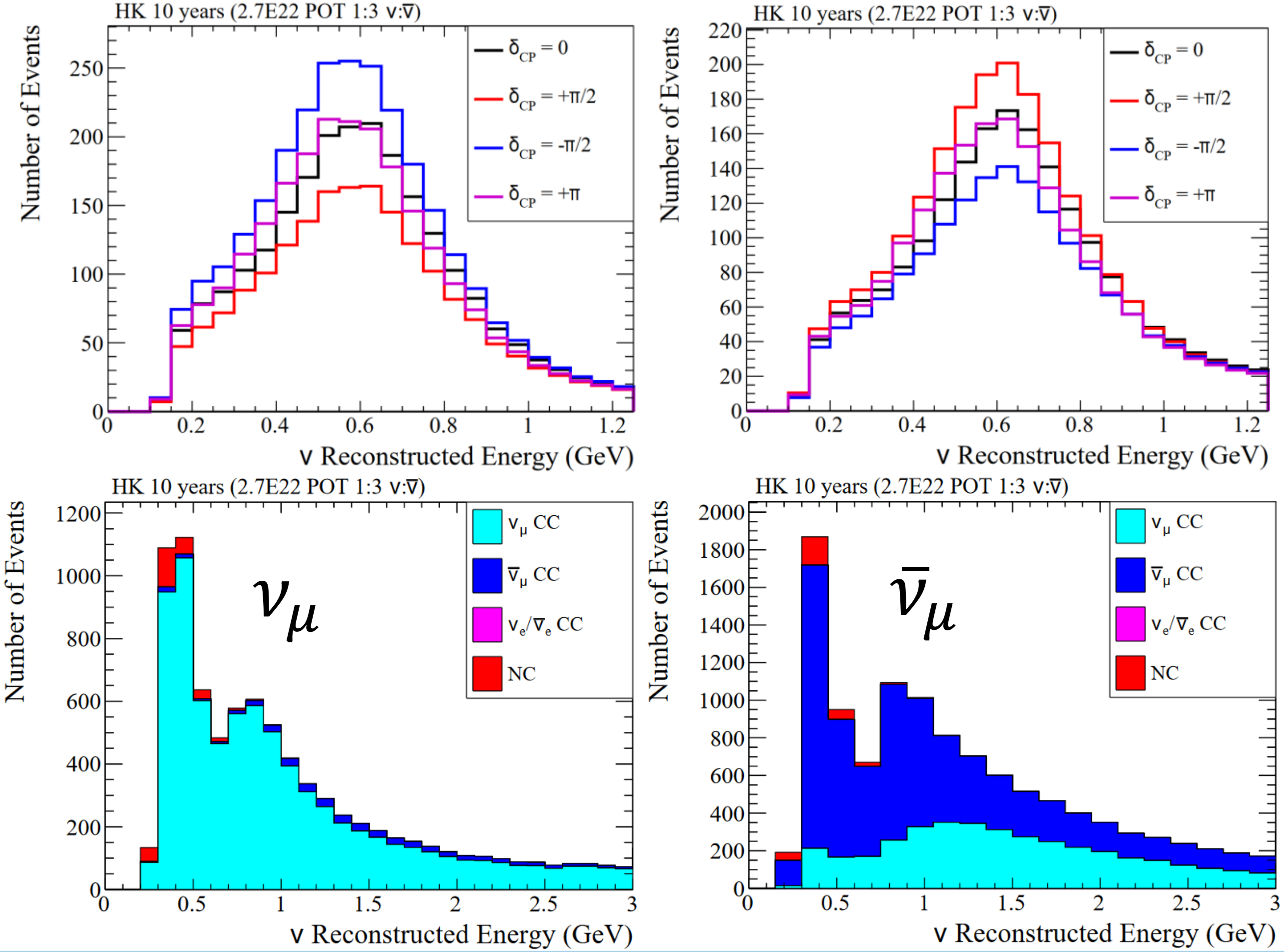




Hyper-Kamiokande far detector event samples

- Use Super-K MC, scaled to HK volume and exposure
- Expect approx:
  - 2300 ν_e events
  - 1800 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$
- Expect approx:
  - 9000 ν_μ events
  - 12000 $\bar{\nu}_\mu$ events

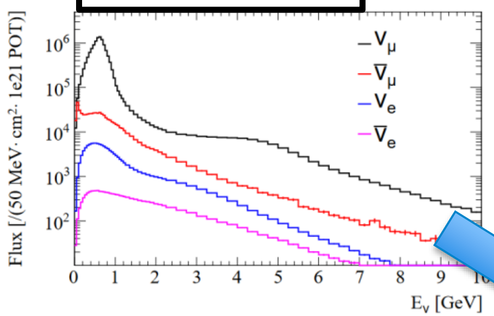
Neutrino beam   Antineutrino beam

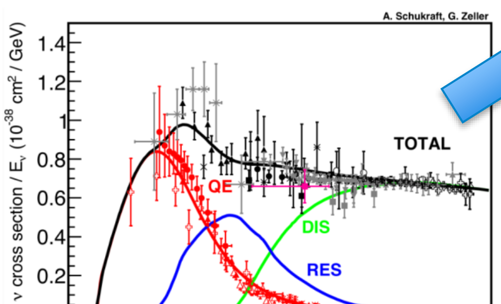


HK Oscillation Analysis

- Currently based on T2K analysis method

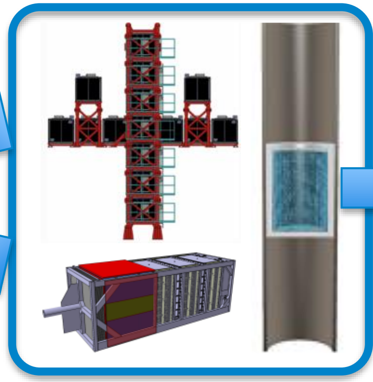
Neutrino flux



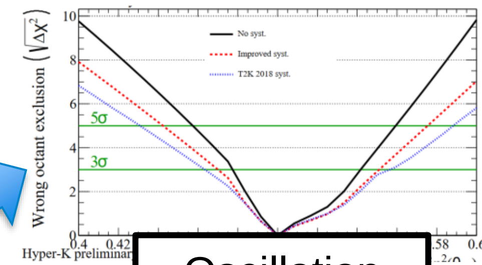


Interaction cross-section

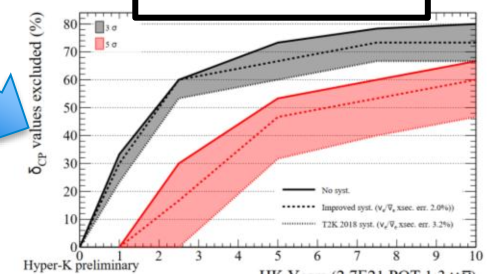
Tune models with near detectors



Fit models to far detector data

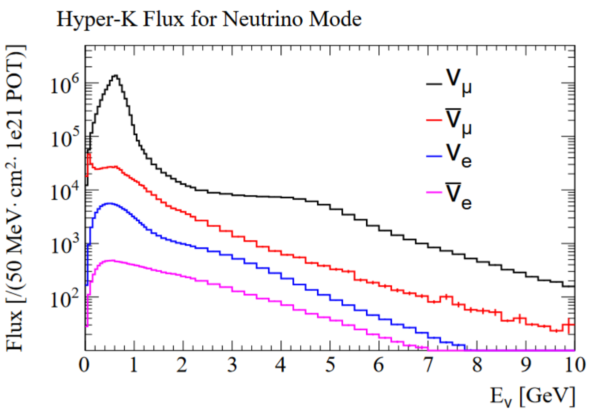


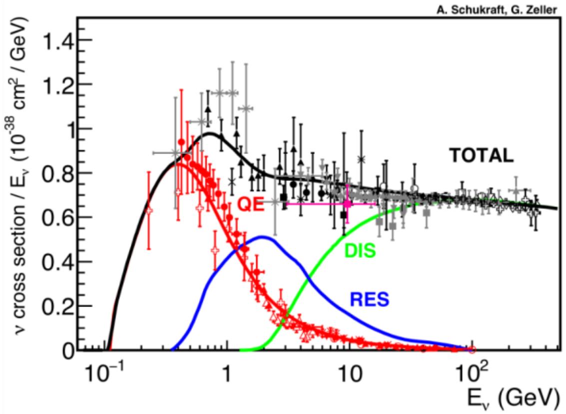
Oscillation parameter sensitivities



Systematic uncertainties

- High statistics experiment, limited by systematics





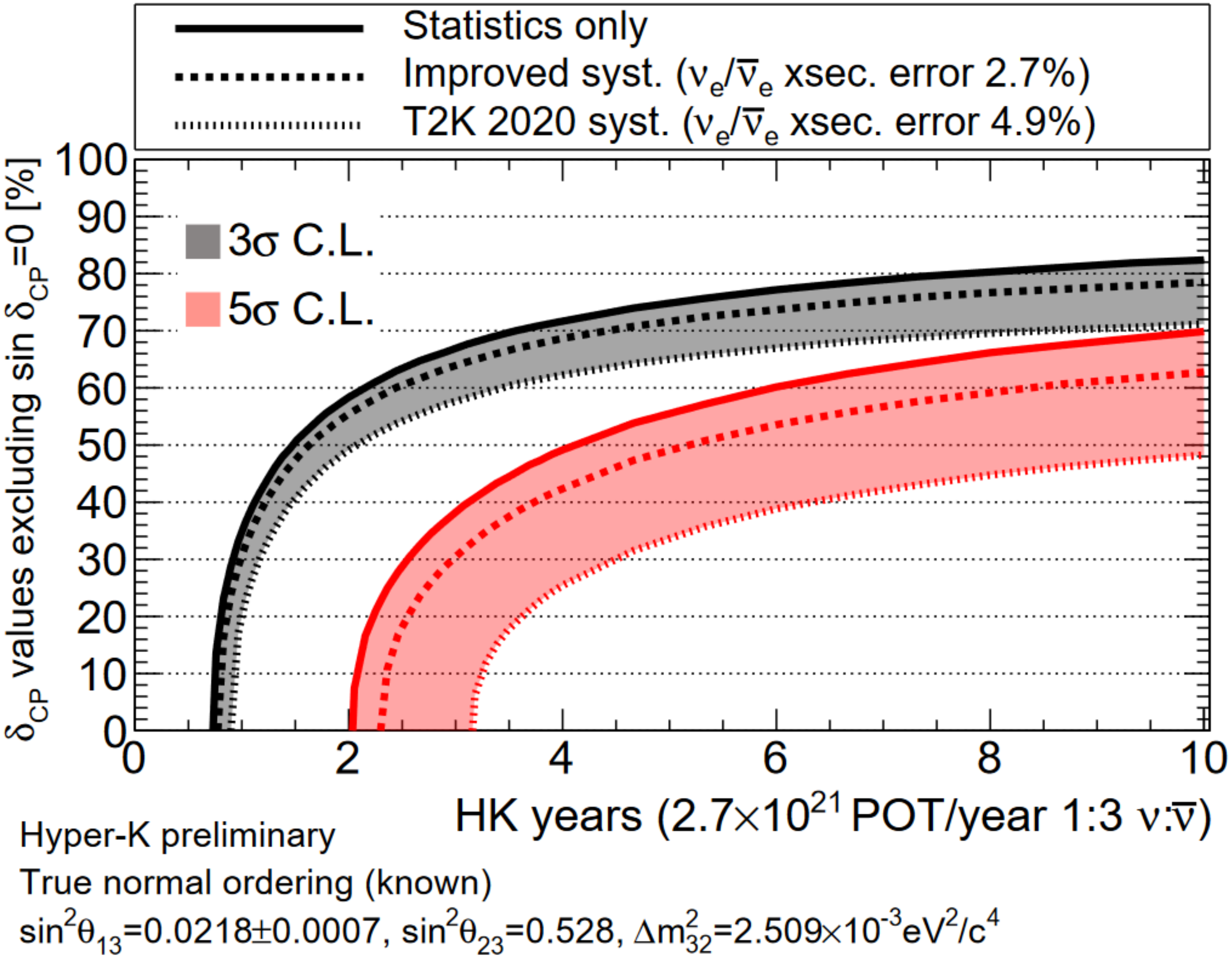
- NA61/SHINE thin-target hadron-production data
- J-PARC neutrino beamline uncertainties

- NEUT 5.4
- T2K 2020 uncertainty model as baseline
  (Eur.Phys.J.C 83 (2023) 9, 782)

- Use T2K near detector fit to provide initial constraint on model uncertainties
- Scale uncertainties to expected Hyper-K near detector performance

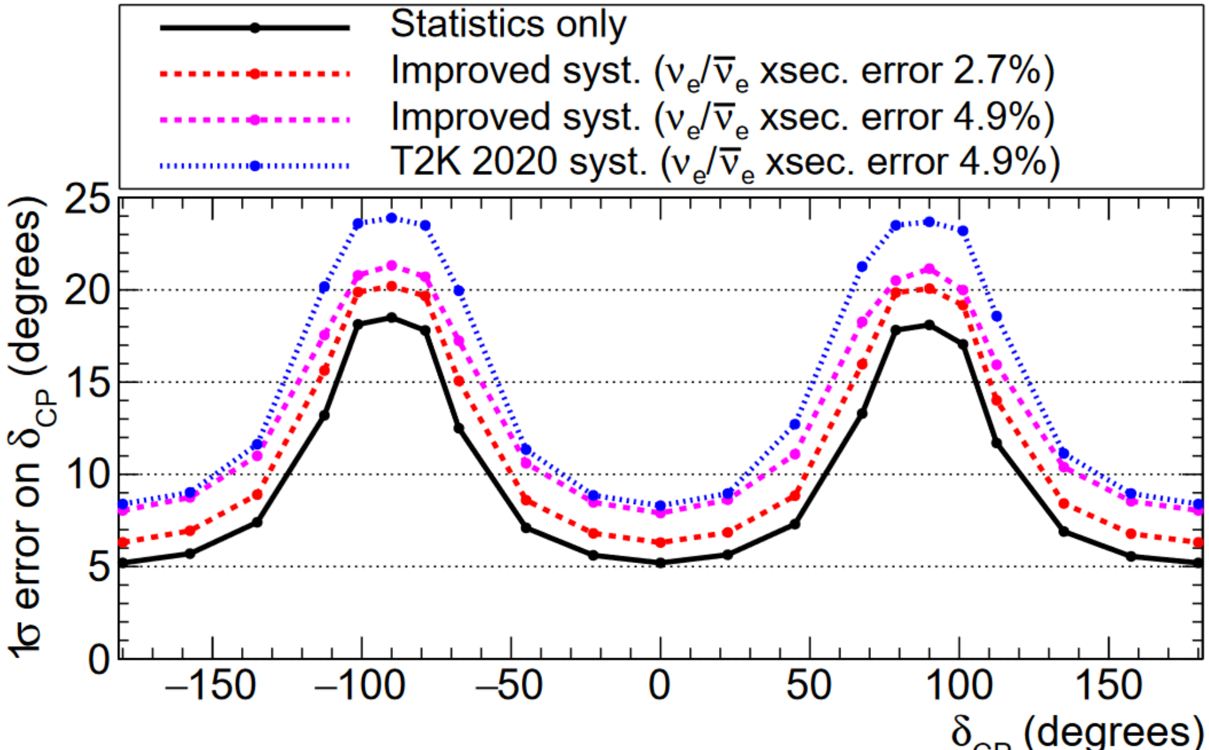
CP violation sensitivity over time

- Percentage of true δ_{CP} values where CP conservation can be excluded as a function of running year
- Can exclude CP conservation for over 60% of true values



Precision measurement of δ_{CP}

- Precision on δ_{CP} depends on true value
- Limited by ν_e spectrum shape uncertainty if **maximal CPV**
- $(\nu_e)/(\bar{\nu}_e)$ cross-section uncertainty limiting factor for **CP conservation**



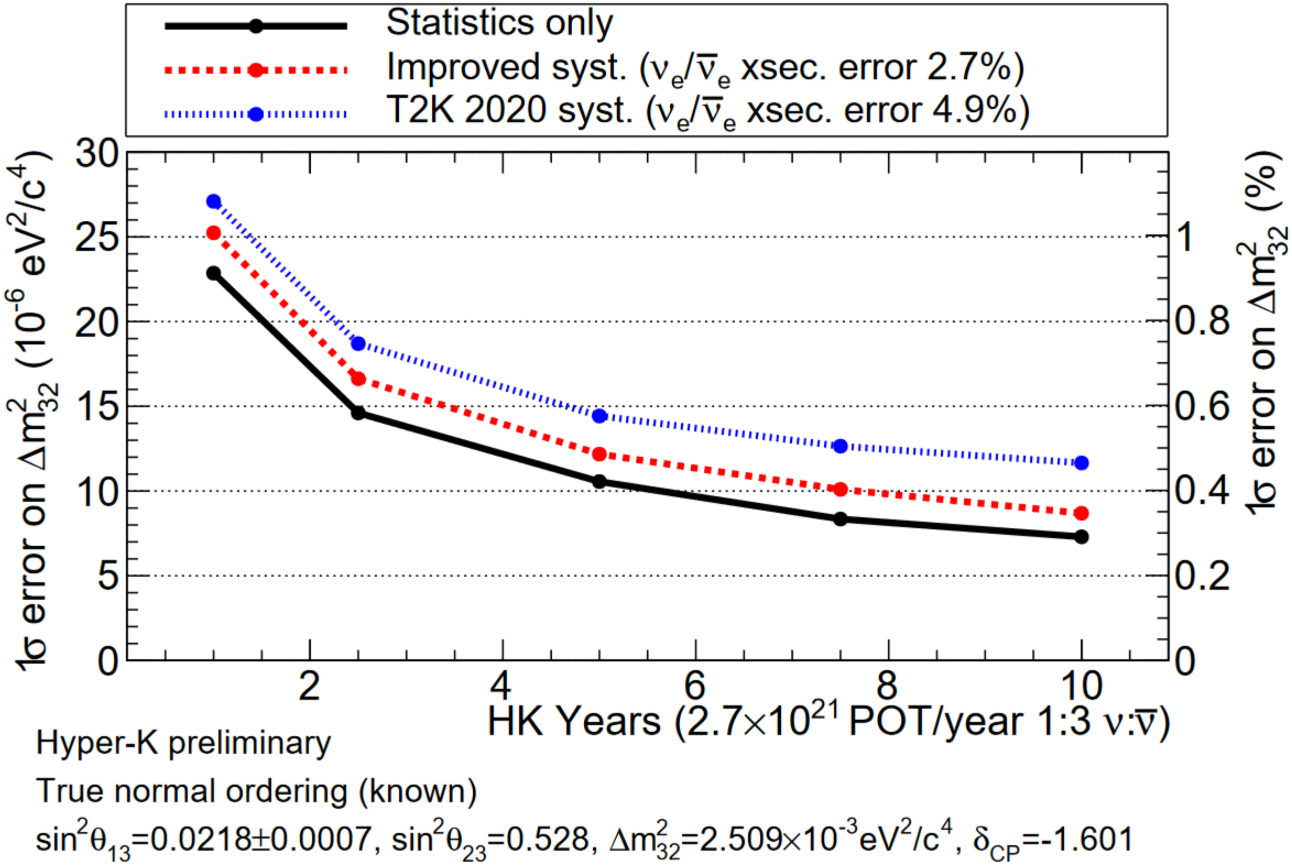
Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\,\mathrm{eV}^2/c^4$

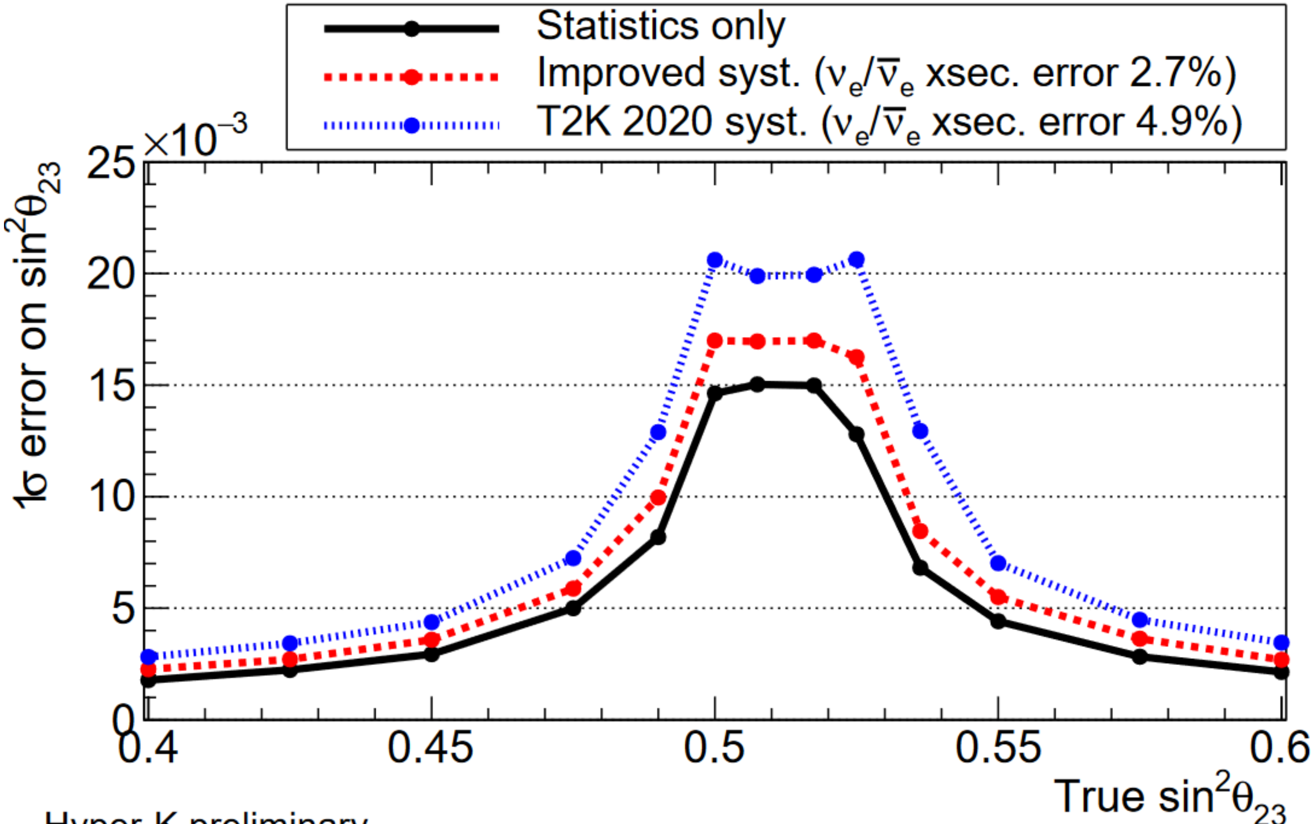
Precision for Δm^2_{32}

- Systematics limited after 5 years or so
- Can achieve <0.5% error after 10 years
- Depends significantly on detector and interaction model uncertainties



Precision for $sin^2\theta_{23}$

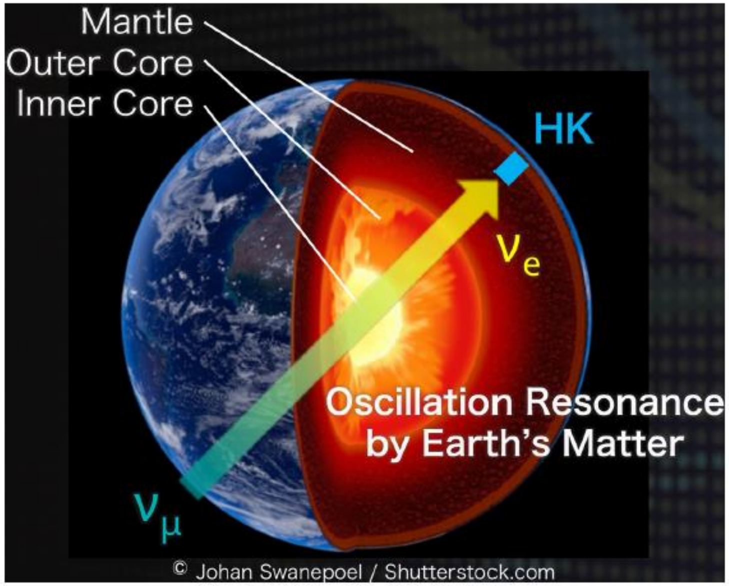
- Precision depends on true value
- Can achieve 3.4% uncertainty at $\sin^2\theta_{23} = 0.5$
- Better than 1% uncertainty for $\sin^2\theta_{23} < 0.45$ and $\sin^2\theta_{23} > 0.55$

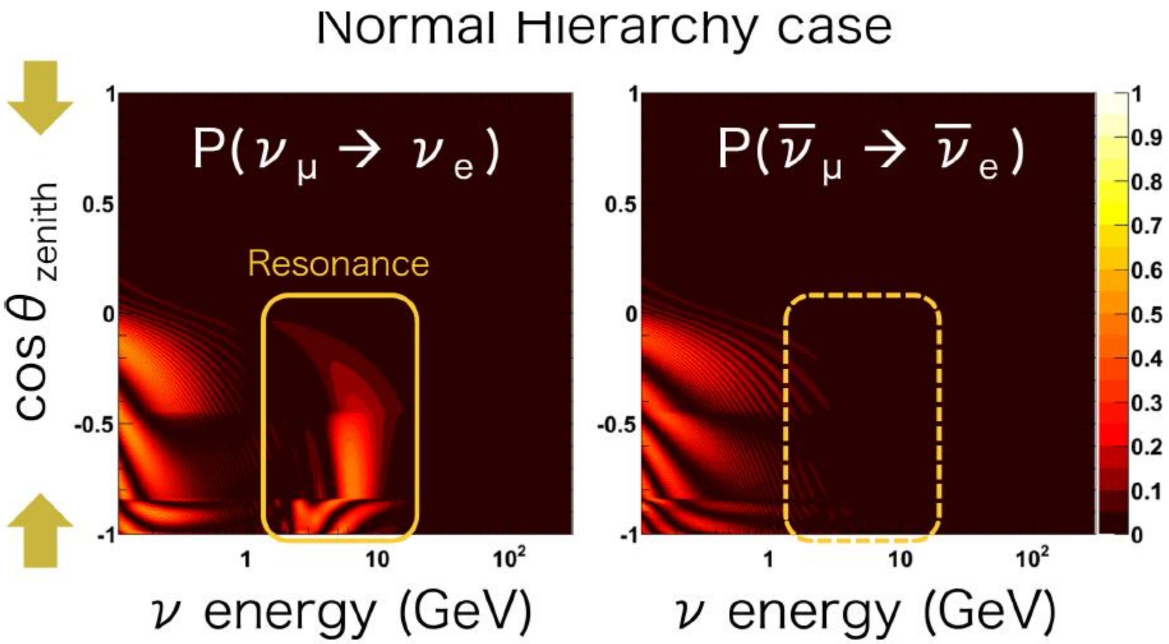


Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}$=0.0218±0.0007, Δm^2_{32}=2.509×10^{-3} eV^2/c^4, δ_{CP}=-1.601

Atmospheric neutrinos

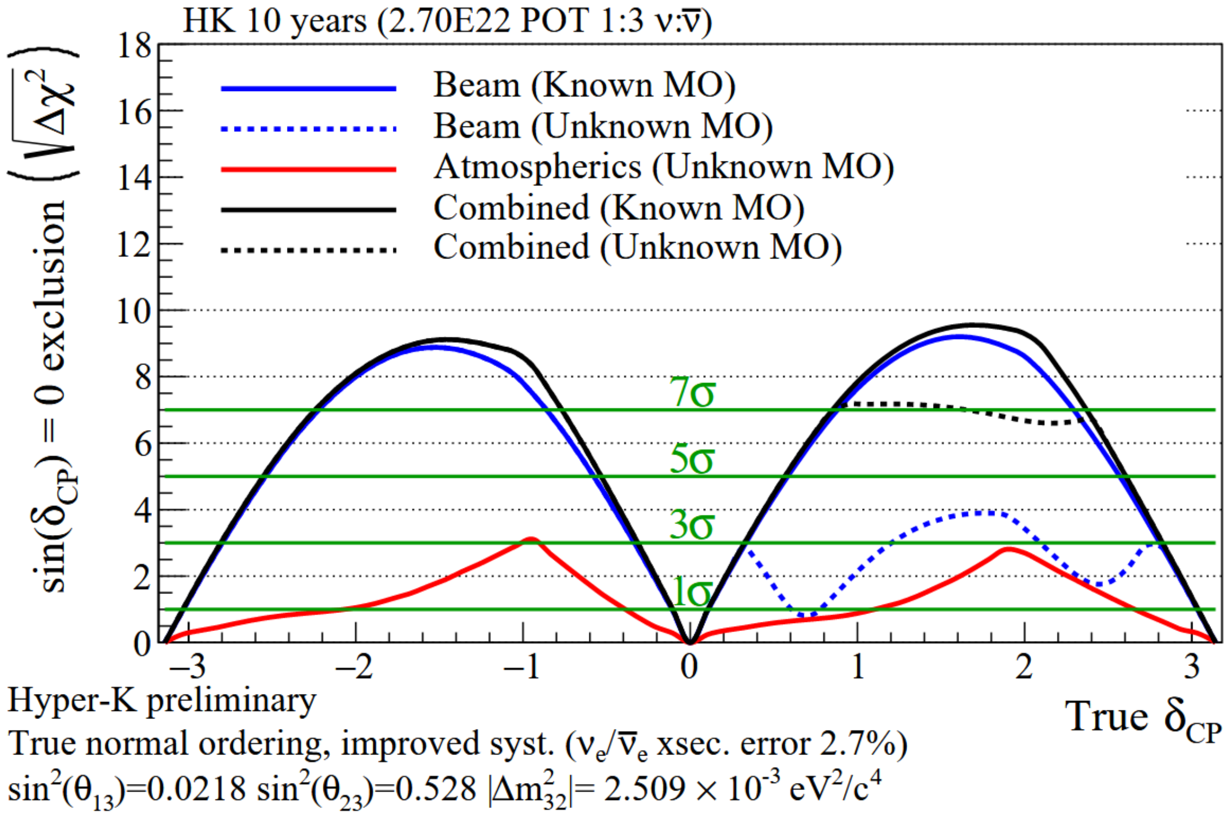
- Atmospheric neutrinos have longer baseline and higher energies – overlap with DUNE and IceCube
- Mass hierarchy determined with upward-going multi-GeV ν_e sample:
  atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline





Atmospheric neutrinos and CPV

- If MO unknown, beam analysis less sensitive for some values of δ_{CP}
- Joint **atmospheric and beam analysis** restores sensitivity above 5σ
- Slight improvement in region of δ_{CP} space that can be excluded at 5σ



Multi-experiment oscillation analysis

- Independent experimental results necessary to confirm discoveries
- However, combining experiments provides many benefits and is necessary for some analyses
  - PMNS unitarity, non-standard interaction searches, other Beyond-the-Standard-Model physics…

- Many experiments have O(GeV) energy neutrinos
  - Hyper-K, DUNE, IceCube
- Many measure same physical parameters
  - Mass splitting (and ordering) from JUNO, alongside above experiments
- Many use same neutrino source
  - Proton beam on target, atmospheric neutrinos

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Many possible correlations between experiment results

Analysis techniques for multi-experiment analysis

- Many possible technical issues in complicated, many-sample analyses
  - Disjoint parameter spaces, many local minima, tension in data, large dimensionality

- Ideally want multiple analysis methods capable of performing fits
  - Bayesian vs Frequentist
  - Marginalisation vs profiling
  - Coverage

- **Personal opinion** – technical advancement will happen within each experiment naturally, should integrate multi-experiment analyses closely to individual experimental analysis frameworks

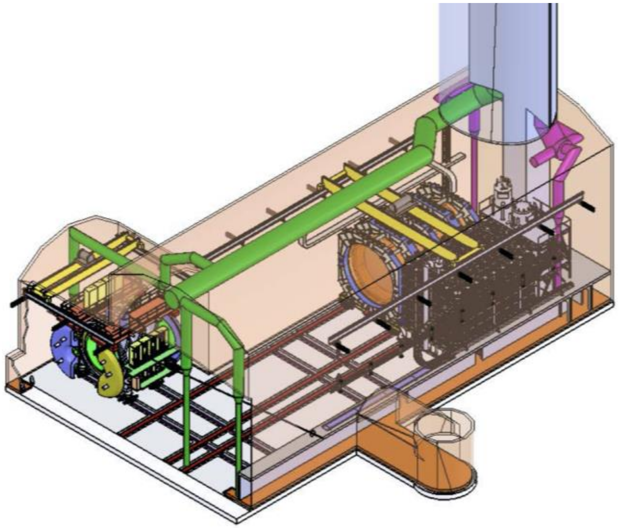
Model tuning for multi-experiment analysis

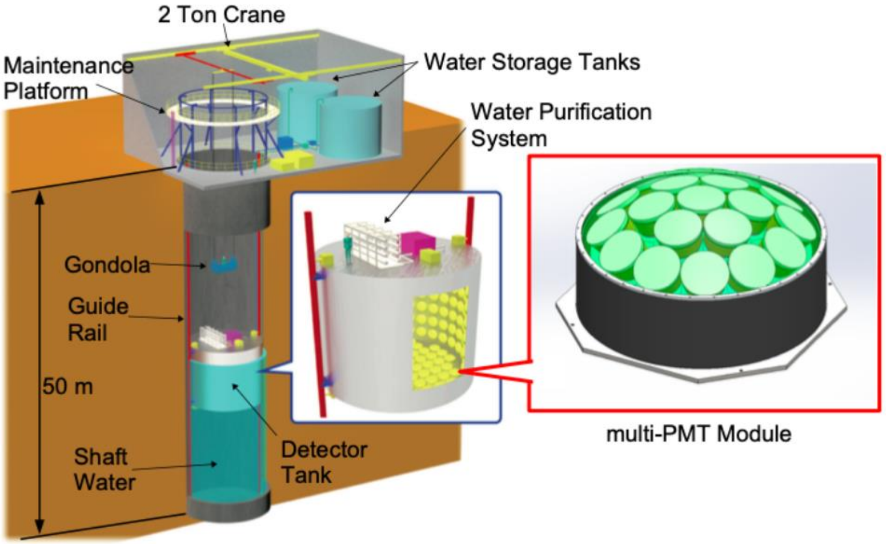
- How do we ensure that the “effective” event rate model used at HK is compatible with that used at other experiments?
  - Nominal model tuned to near detector data
  - Beam energy different to all others
  - Ideally HK-tuned model should give same results as IceCube-tuned / DUNE-tuned etc.

- **Personal opinion** – goal should be to perform “compatibility” checks between tuned event rate models
  - Multi-experiment near detector analyses
  - Potentially opens up new/better BSM searches as well

Off-axis spanning detectors – (nu)PRISM

- Off-axis movement of detectors allow DUNE-PRISM and IWCD to see similar flux
  - Opportunity to test scaling of near detector tunes to other energy regimes
  - Opportunity for experiments to share model tuning
  - Other ways to use near detector information?





Systematics considerations for multi-experiment analysis

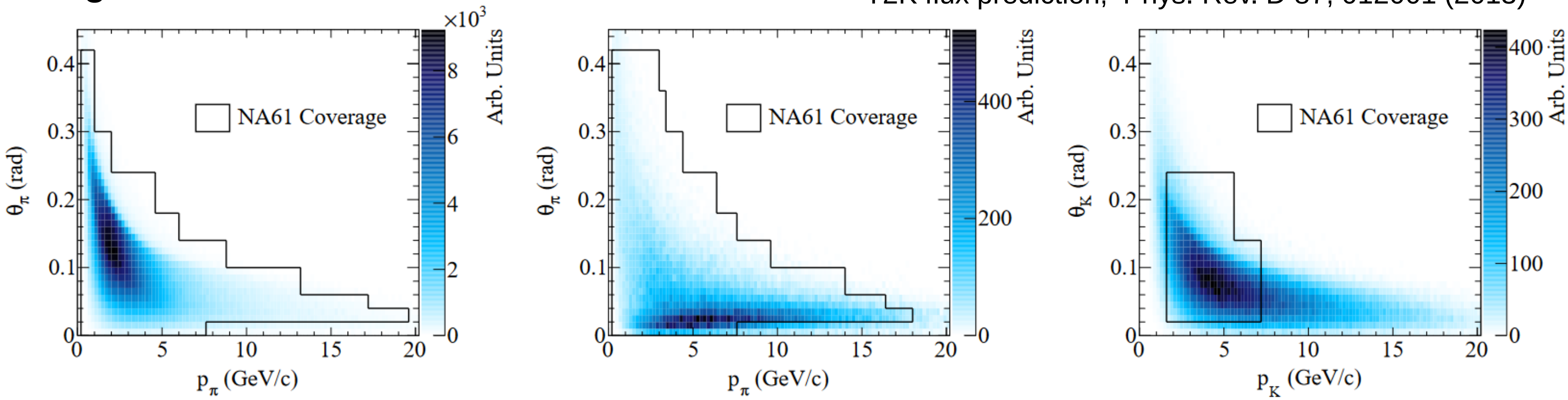
- Systematics-limited experiment(s)
  - Must understand how systematics **affect** different experiments
  - Must understand how correlated systematics are **between** experiments
  - Must understand if we are talking about the **same** systematic!

- Discuss between experiments to ensure analysis choices (made now) do not limit ability to answer the above questions in future
  - Adoption of nuHEPMC as common event format
  - Compatibility with GENIE + NEUT (+ Achilles + NuWro + Gibuu **+** …)
  - Use of NA61 data + uncertainty
  - Meson scattering errors in targets, horns, atmosphere etc.?

Flux systematics

- Expect both HK and DUNE to use NA61 data to tune hadron production from targets

T2K flux prediction, Phys. Rev. D 87, 012001 (2013)



(a) π^+ (b) π^- (c) K^+

- Same detector setup, so potential for correlated uncertainty or bias
- Meson scattering errors in targets, horns, atmosphere…
  – Impact of these uncertainties at experiments varies, but may be important to achieve percent-level uncertainty in a combination

Interaction model and systematics

- GENIE, NEUT, NuWro, ACHILLES, GiBuu…
- Even when generators implement same models you can get different results
  - Interaction is not fully specified by model

- **Personal opinion** – ideally would have experiments able to use many generators
  - NuHEPMC data format a great start

- Alternatively, need to understand how to parametrize systematic uncertainty in models in a common way
  - Understand what degrees of freedom are present and how they affect each experiment
  - Potentially more challenging than using same generators

Summary

- After 10 years data taking Hyper-Kamiokande will:
  - Exclude CP conservation at 5σ for 60% of δ_{CP} parameter space
  - Achieve between 20° - 6° precision on δ_{CP}
  - Achieve 3.6% precision or better on $\sin^2\theta_{23}$
  - Achieve 0.5% precision or better on Δm^2_{32}

- Ultimate sensitivity requires combinations of experiments
  - Increasing overlap between experiments, both in neutrino sources, energies and physics results
  - Experiments limited by systematics, so understanding these is essential

- By starting discussion now we can work to make combined analysis possible in future

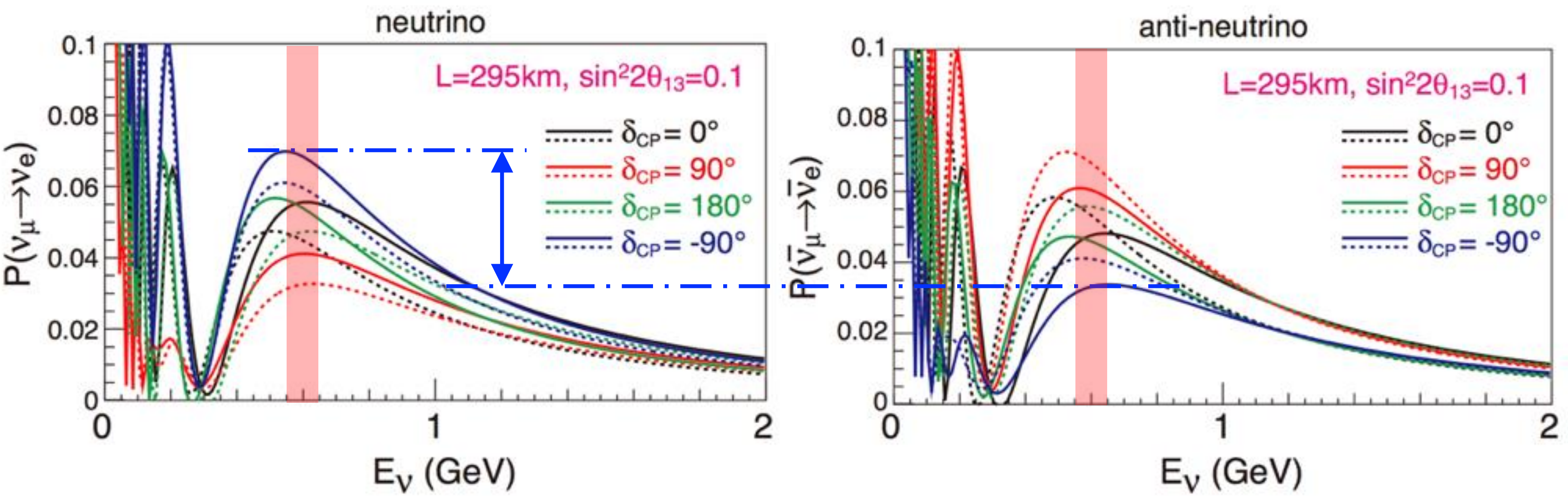
Supplementary slides

Neutrino oscillations

- Measure flavour composition of beam as function of L / E

$$P_{\alpha\to\beta} = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E} \right|^2$$

- Compare neutrino beam and antineutrino beam to test CP symmetry

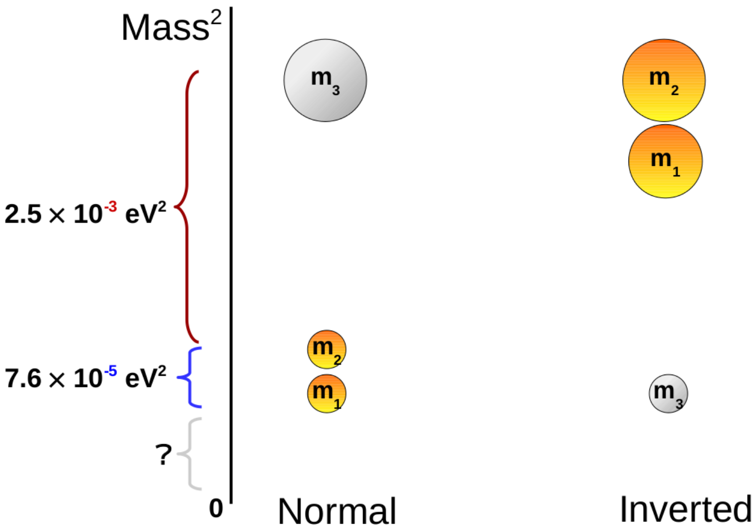


Neutrino oscillation formalism

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

- Three mixing angles, θ_{12}, θ_{23} and θ_{13}
- Two mass splittings, $\Delta m^2{}_{12}$ and $\Delta m^2{}_{23}$
- One CP-violating phase, δ_{CP}



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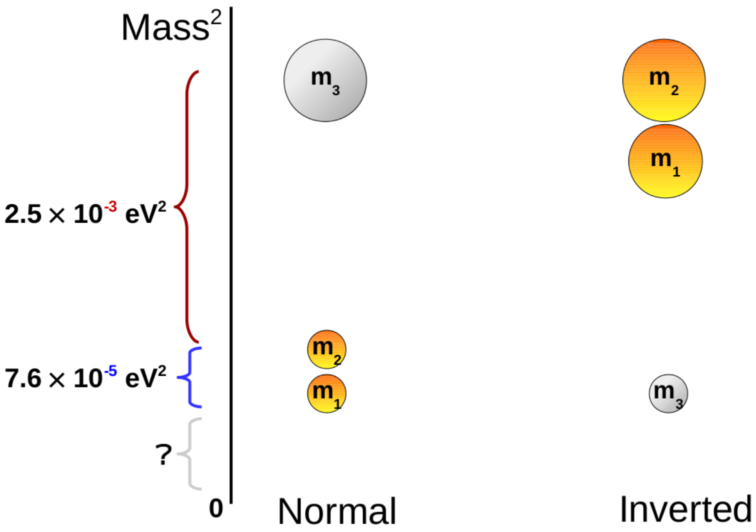
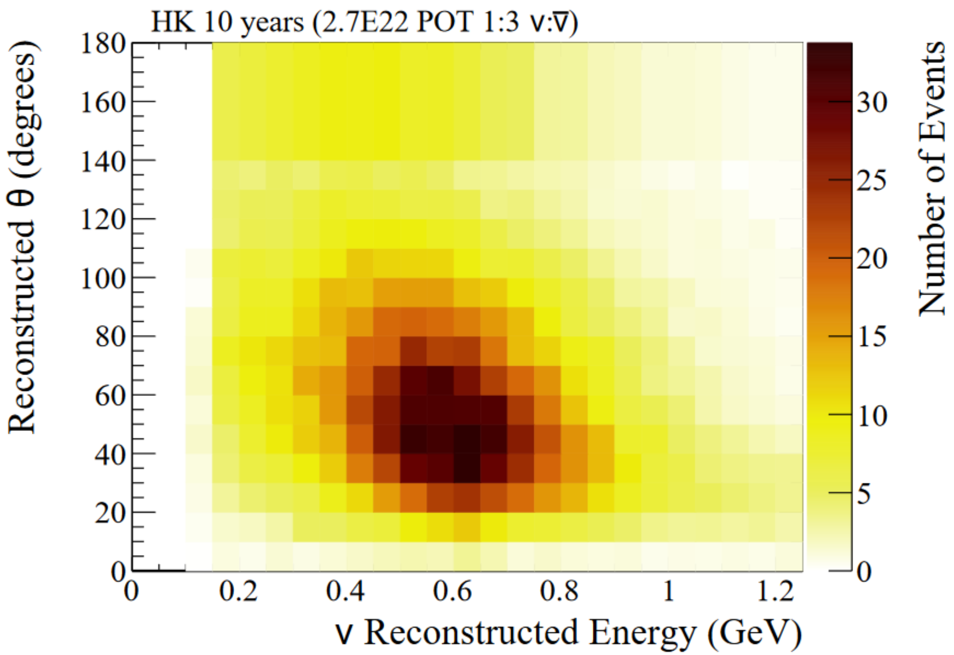
$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

- **Is θ_{23} above or below 45° (octant)?**
- **What is the neutrino mass ordering?**
- **Do neutrinos violate CP symmetry**?



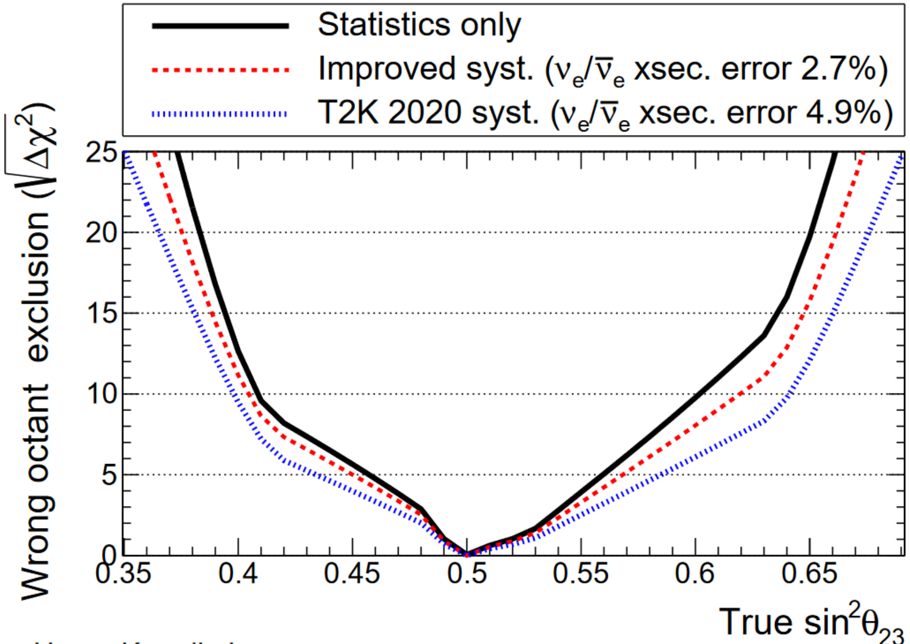
Oscillation analysis fit

- Simultaneous likelihood fit of electron-like and muon-like samples at HK
- Profile systematics and oscillation parameters
- Fit electron-like samples in 2D (reconstructed energy vs lepton angle relative to the beam)
- Muon-like samples fit in 1D as function of reconstructed neutrino energy (assuming CCQE kinematics)
- Include flux and cross-section uncertainties using T2K 2018 near detector fit results
- Far detector uncertainties based on 2018 Super-K systematics



Lifting the $sin^2\theta_{23}$ degeneracy

- All analyses assume 10 years of HK data
  - 1:3 ratio of neutrino beam to antineutrino beam
  - **Not** including atmospheric neutrino sample
- Wrong octant exclusion versus true value of $sin^2(\theta_{23})$
- Estimated systematic uncertainty on muon sample reduced from 4.6% to 1.9% with improved near detectors
- Achieve >3σ exclusion for:
  - $\sin^2\theta_{23} < 0.47$
  - $\sin^2\theta_{23} > 0.55$



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Mass hierarchy determination

- Can exclude incorrect mass ordering at $4 - 6\sigma$ significance (depending on value of $\sin^2\theta_{23}$)